Astro2020 Science White Paper

Direct Imaging of Exoplanets in Nearby Multi-Star Systems

Thematic Areas: ☒ Planetary Systems ☐ Star and Planet Formation

☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics

☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments

☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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1 Introduction

High contrast direct imaging will enable great leaps in our understanding of a wide diversity of extrasolar planets, including Earth-like planets in the habitable zones of their host stars, allowing us to characterize their atmospheres, measure their orbits, constrain their radii, and even map surface features. The capabilities needed for these measurements will simultaneously advance our understanding of debris disks, protoplanetary disks, and planetary formation and evolution. (See white papers by Line et al., Christiansen et al., Marley et al., Domagal-Goldman et al., Dragomir et al., Stark et al., Kopparapu et al., Currie et al., and others.)

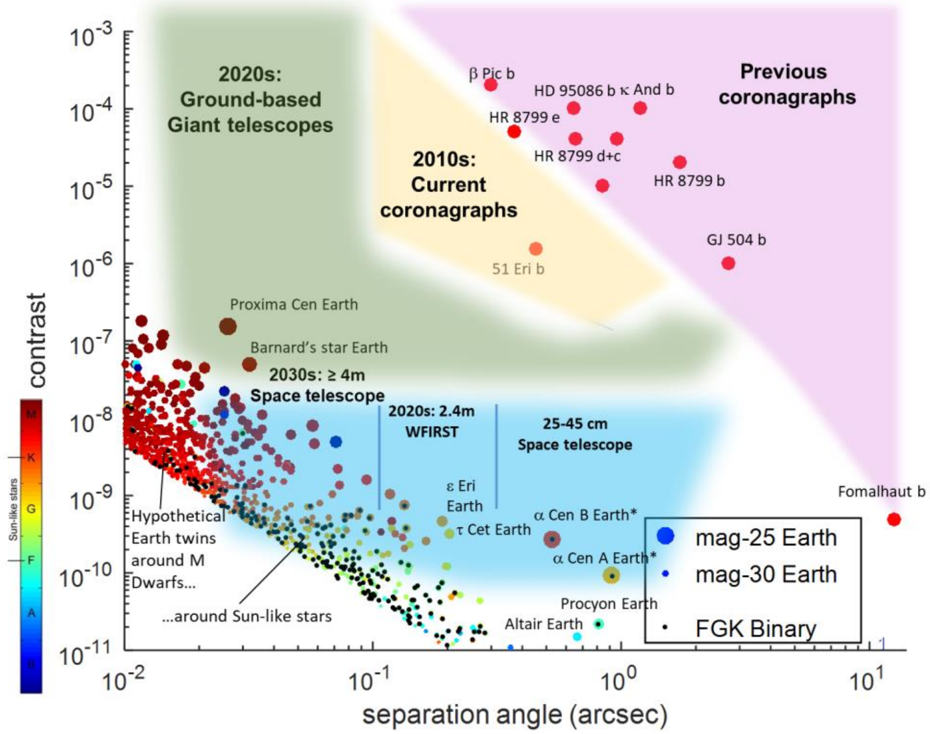

Figure 1. A sampling of current directly imaged planets (upper right, in self-luminous near infrared), and hypothetical Earth twins (bottom left, in reflected visible light). Magnitude legend applies to Earth twins only. Also shown are the capabilities of past, current, and future instrument classes. A large fraction of planets around Sun-like stars are in multi-star systems, marked by black dots for FGK stars.

One representation of the current state and future of the direct imaging field is shown in Figure 1. To date, a few dozen exoplanets and disks have been imaged from the ground and space. Essentially all are young self-luminous giants (a sampling is shown in upper right of Figure 1). The field is moving towards imaging *reflected* light planets, and ultimately the imaging and spectral characterization of Earth-like worlds (bottom left). There is a natural complementarity between space-based and ground-based direct imaging of reflected-light planets: direct imaging of M dwarf planets is well-suited for the ground with ELTs (see white paper by Currie et al.), while the study of planetary systems in reflected light around Sun-like (FGK) and earlier type stars arguably favors space-based missions (focus of this white paper).

In addition, there is a consensus in the community that direct imaging from space is the only way to characterize Earth-like planets around Sun-like stars for a reasonable number of stars [1], with two primary technologies capable of doing this: external starshades and coronagraphs.

In this white paper, we describe the added benefit and opportunities enabled by directly imaging exoplanets in binary star systems, as well as key technical advances needed. We single out this topic in part because there are many interesting binaries that would be prime targets for many missions (see Section 2), but are currently out of reach because the technology to suppress binary starlight is not yet fully mature.

2 Scientific opportunities and context

There are three main ways in which binary star targets impact the science of direct imaging missions: (a) they increase the quantity of available targets and yield of missions (Section 2.1); (b) they increase the average quality of targets because the average target becomes closer and brighter (this is especially true of α Centauri, Section 2.2); and finally, (c) they enable binary-specific scientific pursuits (Section 2.3).

2.1 Abundance of multi-star systems and effects on yields

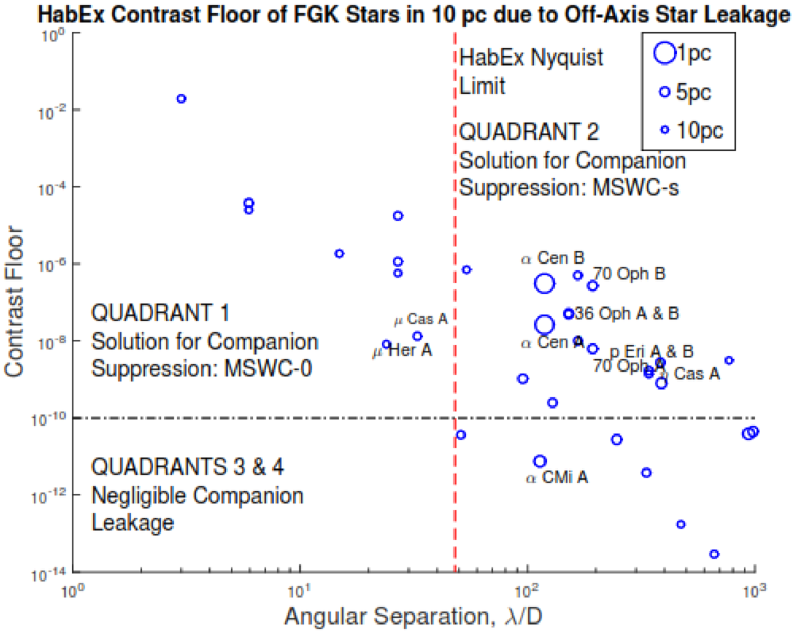

Figure 2. Multi-star systems within 10pc, and leakage from the companion (using the HabEx mission as an example). The x-axis is the binary separation (at current epoch for a 4 m telescope and λ=650 nm) and the y-axis is the contamination suffered by the on-axis target star from an off-axis companion, due to diffraction and optical aberrations (λ/20 rms end-to-end wavefront error and a $f^{-2.5}$ power spectral density). Values above ~10^{-10} compromise the ability to detect potentially habitable planets.

Although most M-dwarf stars are single, the majority of Sun-like and later type stars are in multi-star systems. For example, 5 out of the 7 such systems within 4 parsecs are multiples (α

Cen, Sirius, Procyon, 61 Cyg, ε Ind), and only two are single (ε Eri, τ Cet). Generally speaking, about 50% of FGK stars are in multi-star systems, and ~70% of those (~35% overall) have significant contamination from their companion for Earth-like planet imaging (see [2] and Section 3 for more detail). Thus, a mission that is target-limited would miss 35% of potential targets if it cannot suppress more than one star. For larger missions which are time-limited (such as HabEx and LUVOIR), roughly speaking ~10% of otherwise high priority targets would be skipped due to binarity, and another ~10% would have greatly increased exposure times. Multi-star suppression could enable efficient observations of these stars, therefore enhancing the scientific productivity of these and other missions.

2.2 Target highlight: α Centauri

The αCen system represents a particularly attractive target for direct imaging missions, except for the fact that it is a binary system. Aside from its multiplicity, the A and B stars of the system are unusually fortuitous low-hanging fruits that are 3 times easier than the next easiest target by almost any metric (see Figure 3, left). In particular, the next closest star earlier than M-type (ε Eri) is 2.4 times as far, and is known to have a thick disk that may interfere with detection of small planets. The next star of comparable proximity to α Cen is Barnard's star, which is 1.4 times farther, has a much dimmer magnitude of 10, and has a habitable zone only 30mas wide, about 30x smaller than αCen. In fact, αCenA habitable zone spans such a large angle on the sky (~1") that the *outer* working angle may be more limiting than the inner working angle. The planetary system around αCen would be imaged in at least ~3x higher spatial and spectral resolution (in the photon-noise limited regime) than around any other star, or have at least ~3x SNR for a given spectral resolution. This in particular means that the sensitivity to biomarkers may be much better for planets around Alpha Centauri than for those around any other system.

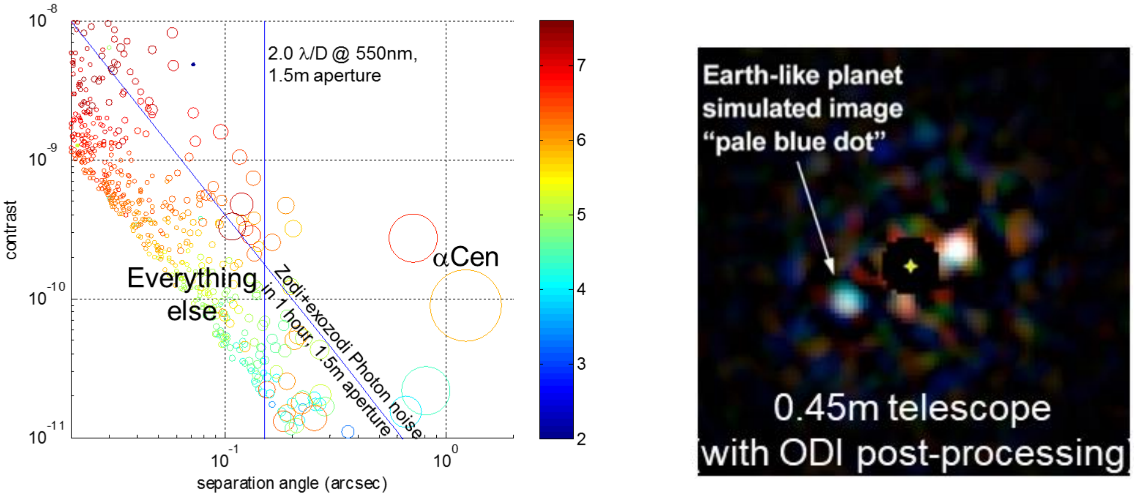

Figure 3. Left: Simulation of an Earth twin at maximum separation around every real nearby star. Circle size and color represent star size and type. Almost any mission would image planets around Alpha Centauri with at least ~3x higher spatial and spectral resolution than any other star, except for the fact that it is a binary. Right: Simulated image of an Earth twin around α Cen A for the ACESat mission concept. Among included effects were zodi, exozodi = 1 zodi, photon noise, telescope jitter.

Furthermore, one of the stars in the system (αCen B) is K-type, with an Earth-twin contrast than can be as high as ~10^{-9} at 0.2" in the gibbous phase. If WFIRST meets its currently expected performance (~10^{-9} 5-sigma contrast at 150 milliarcseconds), and if it can suppress the binary companion to the same level, then it would be capable of directly imaging an Earth twin around α Centauri B.

Theoretically, an Earth twin can also be imaged with a telescope as small as 0.25m (25cm) in ~10 hours, assuming it is equipped with a powerful enough coronagraph and wavefront control system [3,4]. Even at that extremely small aperture, an Earth twin will appear 2.7 λ/D away from the A star at maximum elongation, and have a flux of 1 photon per minute (after accounting for coronagraph and other throughput losses). A larger telescope would add margin, and Figure 3 shows a simulation of imaging a hypothetical Earth twin around α Cen A with a 45cm aperture [5]. Since aCen is 1.3pc away, this is similar to a 4.5m telescope imaging a similar system at 13pc.

The potential existence of a brighter exo-zodi around α Cen (as tentatively suggested in [6]) may of course overwhelm the light of the exo-Earth. However, the unusual proximity and brightness of the target also ameliorates the effects of exo-zodi. Furthermore, α Cen gives us the best opportunity to study structural disk details in much higher resolution than around any other star.

In short, if α Cen was a single star, it would probably be on the top of the target list for any direct imaging mission, and (if it has potentially habitable planets) would probably end up being the science highlight of any mission.

2.3 Binary-specific science questions

In addition to increasing the quantity and quality of targets, binary stars also enable the study of a number of science questions and themes that specifically require observations of binaries (or more generally, multi-star systems):

- Detecting and characterizing the planetary systems in *all* nearby planetary systems, independent of stellar multiplicity.
- What types of planets do multi-star systems have and how do their properties compare to those around single stars?
- What is the planet occurrence rate in binaries, and how does it compare to single stars? (Several papers have treated this subject, such as [7] and [8], and so far the available data comes from transits and radial velocity. Direct imaging will extend these studies to planets which are challenging to detect with transits or radial velocity methods.)
- How do planets form in binary star systems, and how do the formation processes compare to single star systems?
- How do planetary orbits evolve in binaries? There state of models is fairly mature (e.g. [9]), but the observational data is still scarce.
- What types of circumstellar disks do multi-star systems have, how do they form and interact with planets? What effect does star multiplicity have on disks, compared to single stars?

3 Key Advances Needed

3.1 Technical challenges

The main challenge in imaging planetary systems of binary stars is the contamination by scattered light of the companion. Figure 2 shows the magnitude of this contamination for binaries within 10pc, under the assumption of a 4m telescope with $\lambda/20$ rms end-to-end wavefront error and a $f^{2.5}$ power spectral density [2]. 25 of the 70 stars suffer more than 10^{-10} contrast contamination from the companion and 12 suffer more than 10^{-7}. Although the exact amount of contamination depends on many specific details (size of the aperture, type and amount of error, epoch, and location of region of interest), it is clear that a significant fraction of targets will be missed, unless the capability of suppressing the stellar companion exists.

3.2 Binary-star suppression technologies

Several techniques enable binary star suppression, but need further study and development. A number of binary star coronagraphs have been proposed (e.g. [10, 11] and at least one has been used on sky [10]. Such instruments remove contamination caused by diffraction from the companion, but not by the aberrations from the instrument. They are sufficient for science cases where only mild contrasts are required, or where the leak from the companion is mild.

In order to solve the general problem of starlight suppression with a coronagraphic instrument, adaptive multi-star wavefront control (MSWC) is necessary [2, 12-14]. In theory, it is also sufficient to suppress the leak of the second star even with single-star coronagraphs. MSWC, or equivalent, is likely required for any instrument attempting to directly image potentially habitable planets around many binaries, including WFIRST, HabEx, LUVOIR. MSWC is currently being developed [13,14] and is currently at TRL3. It is compatible with the existing starlight suppression systems of these missions, but requires the addition of a mild grating.

Alternatively, a starshade can be used with a coronagraph to enable binary star imaging. If a starshade is used on the off-axis star, then no other special techniques are needed, but MSWC enables the starshade to be used on the on-axis star (with or without a coronagraph) [14].

4 Conclusions

Binary star systems can significantly enhance the science output of almost any space mission that directly images exoplanets, if the technologies to suppress starlight in multi-star systems are matured. The scientific impact of such technologies would be to increase the quantity and quality of targets, as well as to enable answering binary-specific science questions. Enabling binary star targets for HabEx and LUVOIR would make those missions even greater by increasing their yield by 10-20%. Enabling Alpha Centauri B as a target for WFIRST results in a possibility of imaging a potentially habitable planet (if WFIRST meets its expected performance contrast of ~10^{-9}). A ~40cm telescope is sufficient to access the entire habitable zones of αCen A and B.

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